Scientific Graphing

A Review of the Literature

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Abstract

In this review of the literature, we examine the issues related to graphing in science education and the instruction of scientific graphing. The current literature in the field of graphing in science education yields the following thematic elements: computer use, assessment, amount of space devoted, differences between school science graphing and real-world scientific graphing, graph interpretation, and use of graphs to improve understanding. In addition, there is disagreement as to whether graph instruction is best accomplished through graph interpretation or graph construction. Although there are a multitude of studies relating to graph comprehension and interpretation, there are few related to teaching graph construction. In our review, we included information regarding the ways the viewers interpret graphs, including the physical traits of the graphs as well as factors such as viewer's prior knowledge and teachers' skill in graph instruction. Graph interpretation and construction is a valuable skill due to the increasing prevalence of graphs in popular and scientific literature.

A review of the current literature on the topic of graphing in science education yielded the following thematic elements: computer use, assessment, amount of space devoted, differences between school science graphing and real-world scientific graphing, graph interpretation, and use of graphs to improve understanding. In addition, we found divergent claims as to how best to instruct graph comprehension. First, we will examine the overall themes found in the literature and then we will focus on research themes in graphical instruction.

Introduction: Why are graphs so important?

Diagrams and graphs serve as reasoning tools for students to make inferences from data and enable them to comprehend new abstractions (Hardy, Schneider, Jonen, Stern, & Möller, 2005). Hardy et al. (2005) referred to studies where conceptual reasoning was dramatically improved through visual representation using graphs and diagrams (Boulter, 2000; Roth & McGinn, 1997). Graphs are highly relevant because of their importance in the functioning of scientific disciplines. Proficiency in graphing is one of the practices subsumed within the culture of that discipline (Bowen & Roth, 1998). Being able to use graphs as a matter of practice within a science discipline is expected and anticipated. Graphs are typically used to convey information in journals due to their efficiency in demonstrating a lot of information in a relatively small space. In addition, graphs reinforce the mathematical structure of nature so that unequivocal design can be established (Bowen & Roth, 1998).

Graphs play a major role in scientific argumentation in that they assist with reasoning from data to conclusions and claims of knowledge. It is fundamental to scientific literacy for students to have the skills and knowledge to analyze and make assertions about data (Gruber, 2011). The ability to make meaning out of data and correlate it with proper questions extends science literacy beyond general literacy. Scientific literacy is the prerequisite for scientific argumentation and graphing skills are a critical component of that process. Proficiency at graphing enables students to engage in activities as scientists would for reasoning, making judgments and decisions, and solving problems.

Despite the obvious importance of possessing facility with graphs, teaching it remains a problem for teachers. Claiming that "illustrations and graphics are no longer supplementary but a central communicative feature of texts," Driver, Newton, and Osbourne (2000, p. 294) emphasized that the context of the argument should be taken into account. Graphic displays of data assist in the process of analysis. Graphs produce relevant indications of the nature of added statistical work. When statistical data are properly presented, essential elements of the information they represent are revealed that serve as an alternative mode of effectual communication (Li & Goos, 2011). As a result, students with proficient graphing skills are apt to be more successful in figuring out nontraditional statistical problems (Li & Goos, 2011). The true test of graph comprehension lies in aiding students in advancing their ease in use and understanding (Glazer, 2011). For students with effective graphing literacy, selecting graphing criteria depends on three elements: the kind of information to be related, prior knowledge, and expectations of the graph observer (Shah & Freedman, 2011).

Shah and Freedman (2011) heralded the advantage of a perfect graph. They described "A well-designed graph [as] a vivid, memorable, and easy-to-understand depiction of quantitative information" (Shah & Freedman, 2011, p. 560). How then, can the important technique of graph design be taught? The role of graphing in science is as much an educational issue as it is a philosophical one. Students need to possess 21st-century skills such as the ability to work with data, make inferences, and comprehend data to make claims and evaluations (Glazer, 2011). Glazer (2011) argued that this is the most essential of skills. He referred to the growth of technology to be commensurate with the rise in the use of visual representation of data in graphs and tables occurring in all aspects of life. Graphs can be taught in any discipline and are pervasive in science practice, lectures, and textbooks. Despite the ubiquitous presence of graphs, the ability to interpret them lags behind (Glazer, 2011). This is problematic as there has been a significant rise in the prevalence of graphs in both professional journals and daily newspapers and there has been a rise in the number of graphs depicting quantitative data (Glazer, 2011). Therefore, students' must develop their interpretive abilities. It is essential for students to develop the capacity to comprehend pertinent information from graphically illustrated data. Students need to be able to draw out results from reading *within* data, where they pull out accurate information from graphs and communicate it verbally (Li & Goos, 2011).

There is, however, a dilemma in how to teach graph comprehension. One method would be to focus first on graph creation; another method would start with graph interpretation. Creation and interpretation experiences go hand-in-hand. Glazer (2011) suggested that they be taught in a complementary fashion. Numerous variables need consideration in this learning process: students' background, teachers' proficiency in teaching, budget constraints, and differences in curriculum are some of the major considerations (Glazer, 2011). Shah and Freedman (2011) reported that researchers in math education support the idea of bar graph comprehension before they introduce line graphs (Shah & Freedman, 2011). Research can be found in support of instruction in understanding and interpretation first or in graph construction first. We will discuss each position and the accompanying research after an examination of graphing with computers, assessment, space considerations, differences in school versus real-world graphing, interpretation, and graphing for better understanding.

Graphing with Computers

Microcomputer-based laboratories rely on digital sensors and probes to directly collect real-time data and display it numerically and graphically. Graphs are formed instantaneously as data are collected, which allows for immediate feedback and discussion leading students to view the data as dynamic. One salient feature of microcomputer-based labs (MBLs) is that they free students from the menial task of graph production and the tedious work of data collection.

Several studies have explored the use of computers in graphing or MBLs. The real-time feature of MBLs contributed to high school students' better comprehending distance and velocity graphs in Brasell's (1987) study. Mokros and Tinker (1987) found that MBLs helped facilitate graphical communication by using multiple modalities, pairing events with their symbolic graphical representations in real time, providing genuine scientific experiences, and eliminating the drudgery of graph production. It was found that a semester-long MBL program provided students with the skills to correctly evaluate the shapes, slopes, and data of graphs in a study completed by Nachmias and Linn (1987). Conversely, Beichner (1990) determined that there was no educational advantage in using an MBL over traditional graphing instruction. Beichner found that student control over a kinematics motion lab may be a more important component to the learning experience than mere visualization of the event.

MBL systems lend themselves to immediate gratification, where students can modify test conditions and motivate them to derive their own "what if" questions as opposed to predetermined ones. MBL nurtures students' interactions with graphs and data and encourages them to confront problems with interpretation. The success of MBL use depends upon the teacher's proficiency in working with students' experience and conceptual growth. However, the automatic graph production could deter students' understanding because they do not directly learn how the graph is constructed (Glazer, 2011). Glazer (2011) suggested that at least it provides an immediate chance to evaluate students' understanding of both math and science concepts in a scaffolded investigation.

Another opportunity to use computer-generated data is the use of authentic data. Teaching with authentic data is a strategy to incorporate real-world information into the classroom (Bell, Fowler, & Stein, 2003). There is a benefit to using actual scientific data; however, the data is for scientists, not classroom teachers. Bell et al. (2003) touted the use of real-time or near-real-time data because such data support the link between school science and real life.

The integration of multimedia with human body movement creates a whole new dimension of learning graphs. Anastopoulou, Sharples, and Baber (2011) sought to determine the effects of multimodal interactions, or the combination of sensory input with communication modalities. Another computer-assisted graphing modality is kinesthetically mapping movement to features of a graph. Anastopoulou et al. (2011) proposed that students determine meaning from mixed modalities to build conceptions about the world. Putting this into practice results in a vision of students using their arms and legs to communicate understanding by creating symbolic representations that directly match their own movement to features of the graph. Learners create stronger conceptual links by building on personal action prior to being lost in the abstraction of a graph.

Assessment of Graphing Skills

Assessment of graphing skills was another area of focus in previous research. McKenzie and Padilla (1986) described the development of a test of graphing skills (TOGS) for middle and high school students. The TOGS was found to be a valid and reliable instrument by a panel of experts for measuring graphing abilities. Berg and Phillips (1994) explored the relationship between logical spatial reasoning and graphing abilities. They found that middle and secondary students who possessed an understanding of Euclidean spatial structures such as multiplicative seriation and multiplicative measurement had better graphing abilities. Assessment indicated that subjects with proportional reasoning did better in many graphing situations and that horizontal and vertical frames of reference were significantly related to the ability to locate points on a graph without a grid.

Berg and Smith (1994) compared multiple choice and free-response assessments of students' graphing abilities and found significant differences in correct responses. Their results suggested that multiple choice tests (with prescribed responses) that assess graphing ability may not be valid because free-response graphing assessments allow subjects to demonstrate their own rationale. Roth and McGinn (1997) presented an alternate view of graphing assessment by suggesting that graphs are semiotic objects, rhetorical and conscription devices. Their perspective situates graphing as a part of a social community practice and, as such, does not have absolute criteria. Roth and McGinn (1997) argued that graphing ability as a cognitive value lies in social practices rather than individual minds so we need not be concerned with the correct methods of graphing.

Space Devoted to Graphs in Journals

Cleveland (1984) and Smith et al. (2000) investigated the amount of space devoted to graphs in varied research journals. Cleveland (1984) found that natural science journals used more graphs than mathematics or social science journals. He also found that of 377 graphs published in a volume of science, errors in graph construction, degraded images, inadequate explanations, and problems with visual discrimination impugned the integrity of the graphs. Smith et al. (2000) found that content journals in the areas of chemistry and physics had a higher fractional graph area (FGA) than biology, medicine, psychology, economics, and sociology, respectively. Smith et al. (2000) found that "The use of graphs, as measured by the proportion of journal page space devoted to them, appears to be a sensitive index of the hardness of scientific fields, whether at the level of entire disciplines or at the level of specialty subfields" (p. 30).

School Science Graphing is Different From Scientific Graphing in the Real World

Researchers in this field found differences between school science graphing and real-world scientific graphing, but provided varied explanations for it. Wavering (1989) demonstrated that students undergo logical reasoning growth as they advance to higher grade levels and demonstrate increasingly more complex understanding. Students in Wavering's experiment were asked to make three different types of graphs (positive, negative, and exponential), to identify a pattern, and to state a relationship if one existed. Wavering (1989) found that student responses had implications for teaching graphing, specifically that data need to be readily scaled and ordered, data should be generated from student experiments, and students should manually create graphs and not be reliant on computer generation to improve their logical development. Roth and Bowen (1999) examined tests and fieldwork of middle school and university students as well as preservice teachers and science professionals in order to gather evidence about their graphing competencies. They also conducted a text analysis of high school biology textbooks and ecology journals. Roth and Bowen (1999) found that there was a clear difference in the graph-related practices of science professionals who must create graphical representations for their work and others. Further, the didactic practices of high school textbooks and university lectures diverge from the graphing practices found in scientific journals. These findings appear to contradict Wavering's (1989) earlier findings that increasing experience leads to more complex understanding.

In a later study Roth, Bowen, and McGinn (1999) compared graphs in ecology-related journals with those in high school biology textbooks and found that the journals provided more resources to facilitate graph reading and more elaborate descriptions and interpretations of graphs than the high school textbooks. In keeping with Wavering's (1989) finding that data should be generated from student experiments, Huber and Moore (2001) presented a model for extending limited hands-on activities into inquiry science lessons with collection of data and the presentation of a graph and culminating writing or speaking activity in order to adopt real-world graphing procedures. Roth (2001) examined textbooks and lectures and observed that they make "the world appear to be typologically decomposable (into variables) which have clear, mathematically fully determined relationships" (p. 5). Enculturation into specific graphing practices was found to exist in textbooks and lectures, which differs from authentic science in actual settings.

Postigo and Pozo (2004) found that there were different types of graphic information (explicit, implicit, and conceptual) where participants' performance varied according to their knowledge of the domain. Postigo and Pozo supported Wavering's (1989) earlier findings by observing that participant performance of graph and map reading also improved with their educational level. Pozzer-Ardenghi and Roth (2010) argued that all representations in text (graphs, tables, photographs, and equations) are situated and contextualized within authentic science settings and students may not have access to these in their daily school activities. They argued that reading graphs and other inscriptions in a science context is a social practice, and thus support findings by Roth and Bowen (1999) and Roth et al. (1999).

Graph Interpretation

The interpretation of graphs was a theme investigated by several researchers. Lohse (1993) described a computer program that predicted response time for subjects to interpret and answer questions posed on a graphic display. This was accomplished by assumptions about the sequence of eye fixations, short-term memory capacity and duration, and the degree of difficulty in acquiring information in each glance. Bowen, Roth, and McGinn (1999) found that the graphing activities of student groups lacked distinction in scientific terms and data-specific information, and as such, did not aid students in developing specific graph interpretation skills. On the other hand, scientists' graphing activities were characterized by experience-based interpretive resources and practices.

Bowen and Roth (2002) analyzed graphs found in professional journals and high school and college texts. They found that alterations made to the graphical inscriptions as they were moved from professional journals to textbooks confounded readers' ability to interpret them. They also interviewed four people possessing a bachelor's degree as to their interpretations of graphs found in the books and journals. Bowen and Roth (2002) found that the greater misinterpretations of graphs in textbooks versus that in journals was due to the fact that there were fewer resources for interpretation in textbooks, and therefore, textbooks are more ambiguous despite changes made to render the graphs less complex. Shah and Hoeffner (2002) found that the major factors that influence viewers' interpretations of graphs are the visual characteristics of the graph (format, animation, color, size, use of legend), a viewer's knowledge about graphs, and a viewer's knowledge about the content of the data in the graph. In a later study, Bowen and Roth (2003) found that preservice elementary teachers and science graduates did not independently graphically summarize or interpret data presented. They argued that scaffolded, research-oriented classes rather than lecture-based science courses are required to teach this important skill. Tairab and Al-Naqbi (2004) examined a group of high school students and found that students' interpretation of graphs was superior to their ability to construct graphs. Lehrer and Schauble (2004) described a study of fifth graders who learned about distribution while modeling plant growth at the population level. The aggregate of (plant) cases provided the data and students read the shapes of distributions as different variables, like the amount of light or fertilizer, which were shown to be mechanisms that acted on the plant population. These investigations supported students' interpretations of the distribution graphs.

Graphs Aid in Understanding

A theme found in several science education graphing articles is the notion that graphs improve understanding. Wainer (1992) discussed the historical role of graphical displays on important discoveries (continental drift, source of cholera epidemic, armor plating of fighter planes after mapping bullet holes of returning aircraft), the three levels of information that form the theory of display (elementary quantitative questions, intermediate trend questions, and overall data structure questions), and ways to improve the quality of display. Bartiromo, Finley, and Etkina (2010) examined physics student answers to one open-response assessment question and found that at least two response graphical representations were necessary in order to provide sufficient evidence of student understanding as students may provide single incorrect representations or representations that lack sufficient reason. Neuner-Jehle, Senn, Wegwarth, Rosemann, and Steurer (2011) found that patient understanding improved when doctors used visual and numerical representations (as opposed to singularly verbal) in their explanations of patient cardiovascular risk. Yoon (2011) provided seventh-grade students with social network graphs to influence their peer decision-making strategies in order to access information about socioscientific issues. Students shifted from socially driven mechanisms (without social network graphs) to reflective, information driven mechanisms (with social network graphs) in order to choose with whom to interact in order to gain more knowledge about socioscientific knowledge.

Three main levels of graph interpretation have been identified: elementary comprehension where specific data points are extracted from the graph, finding trends and relationships in the data, and extrapolating from data and analyzing relationships (Glazer, 2011). These levels correspond to what students need in order to read into, between, and beyond the data (Sharma, 2006). Students have difficulty on the higher order thinking skills (Sharma, 2006).

One challenge of understanding graphs is that too often they are interpreted as pictures; students tend to accept them as literal transformations of data instead of the abstraction they really are (Glazer, 2011). Getting into the data and understanding behind the scenes is what Li and Goos (2011) alluded to as being the prerequisite for students to embrace data as their own, "reading *between* the data therefore requires students to study data relationships and to make comparisons between different pieces of data" (p. 262). The visual representation of data makes a big difference in its interpretation. Glazer (2011) reported that comprehension of graphs is improved when the graphs are constructed by experts or with graphing software. The implication here is that high quality graphs take into consideration the reader's prior knowledge and expertise when they are created.

A skill essential for determining the relationships between variables is the ability to transition between a physical event and its graphic representation (Hardy et al., 2005). The next step is being able to verbalize these understandings. Translating graphs requires one to describe in words the physical appearance of the graph. Interpreting graphs means to reorganize the information and scrutinize the relationships as specified by axes and scales and make explicit connections between them and the context of the data (Li & Goos, 2011).

Graph comprehension skills need to support inference making, or using cognition to transform the data to create relevant inferences for a particular graph. Shah and Freedman (2011) found that individuals who are skilled at making graphs infer relationships about variables better by viewing familiar data and noting graph structure. Inference generation relates to graph complexity. Simple graphs foster few inferences because the paucity of data enables the viewer to easily retrieve data. Conversely, complex graphs frequently spawn inferences because the viewer must decide which information to encode and what mental calculations need to be made to clarify the information (Shah & Freedman, 2011). Students with high graph competency may be more, not less affected by graph format: "Simple graphs typically require individuals to retrieve a small number of facts that can easily be remembered, whereas complex graphs frequently require making decisions about what information to encode and mental computations and inferences to simplify the information depicted" (Shah & Freedman, 2011, p. 564).

Friel, Curcio, and Bright (2001) identified four essential factors affecting graph comprehension: purpose for using graphs, discipline, reader, and task characteristics. Familiarity with graph content reinforces the potential effect on what the viewers perceive as learning goals. In complex graphs, the observer may simplify a connection from data presented, for example, in order to avoid complicated mental calculations, but simply to derive a relationship. Being familiar with the content may assist the viewer in monitoring the information because familiar viewers expect certain relationships to be depicted. Also, knowing something about the graph's content tunes the viewer in to possible errors (Shah & Freedman, 2011). When a person has enhanced skills in comprehending graph content, the format of the graph's display is less of a factor than for lower skilled viewers. Higher skilled viewers may be capable of making the correct inferences no matter what the format (Shah & Freedman, 2011). Shah and Freedman (2011) also noted that it is possible that the opposite occurs; highly skilled observers are more affected by the graph's format because they are able to appreciate and anticipate the depth of information residing in a complex graph. Creating a mental schema of a graph has to do with the use of reasoned judgment about essential and nonessential properties of the graph (Li & Goos, 2011). While a complex graph may require more cognitive effort to understand, it allows a possibility for the viewer to make a greater number of "comprehension goals" (Shah &Freedman, 2011, p. 563). The complexity of the graph requires the observer to simplify or make inferences from the data. Shah and Freedman (2011) distinguished the forms of prior knowledge at play in graph comprehension as "domain-specific familiarity with the content depicted in the graph and a domain-general knowledge about graphs per se" (p. 562). They hypothesized that these two forms of prior knowledge are related to inference generation activities in graph interpretation. Domain-specific content familiarity will have an effect on the observer's comprehension goals (Shah & Freedman, 2011).

Glazer (2011) also found that background knowledge affects graph comprehension. When present, it can lead to either good or bad consequences. Background knowledge provides nonexperts with the opportunity to see relationships in the data even when it is not definitively represented, which in turn, can lead to misinterpretation by seeing relationships that are not there. Viewers rely on prior knowledge of the content rather than the information presented in the graph to draw conclusions, thus resulting in bias and errors in graph interpretation. The problem is not as pedestrian as it seems; even scientists fall victim to misinterpretation of graphs. In a study of graph interpretation by scientists, errors were made in graph comprehension when the scientists were unfamiliar with the content being portrayed (Glazer, 2011). Similarly, when students are familiar with the content portrayed in a graph, their descriptions tend to focus more on the relationships. However, when they are unfamiliar with graphs, students describe trends less often and mention only the maxima and minima (Glazer, 2011).

Another difference between those with background knowledge and those without is that when anomalous data are represented in graphs, they are passed over by novices, yet experts cue in and attempt to explain their existence. Keeping in line with this trend, casual descriptions of data were offered by viewers of graphs when they contained unfamiliar information, but they were more likely to explicate meanings when faced with familiar data, including circumstances when they possessed graphing and scientific literacy skills (Glazer, 2011). It appears that weakness in content knowledge prohibits students from looking beyond data points to explore information in depth (Glazer, 2011). An excellent example of this was provided by Bowen and

Roth (1998), who analyzed the difficulties undergraduate science majors had in understanding lecture content that utilized graphs. The students were at a disadvantage in being able to comprehend the content when compared to the instructor. Although that study was done at the postsecondary level, the similarities with kindergarten through Grade 12 education are apparent.

Graph interpretation can be further confounded when the displayed data relates information that reveals qualitative relationships, a more difficult pattern to interpret than more obvious quantitative relationships. Bowen and Roth (1998) also noted that personal definitions of terms and labels used on graphs may influence comprehension.

The visual representation of data also affects interpretation. Glazer (2011) reported that comprehension of graphs is improved when they are constructed by experts or with graphing software. High quality graphs take into consideration the reader's prior knowledge and expertise when they are created (Glazer, 2011). The manner in which information is graphically displayed affects how data are interpreted, as in x-y graphs, bar graphs, and 3D displays (Glazer, 2011). The need to make mental calculations can also lead to comprehension errors. While x-y graphs are simpler, they can also cause bias; whereas bar graphs are neutral (Glazer, 2011). X-Y-Z graphs, despite their wealth of information, tend to overlook data in the *z* dimension. Yet different graph types serve various purposes: bar graphs show discrete comparisons and pie charts show proportions (Glazer, 2011). Color can also be used to represent data characteristics such as blue for males and red for females, which helps viewers to track changes and patterns. Color use offers support to graphical interpretation and should be used cautiously, depending on agreement within the community of users (Glazer, 2011).

Graphical understanding can be confounded by asynchrony. *Asynchrony* refers to a disconnect between a reference made to an area on the graph and a physical gesture directed towards a different area on the graph. This situation occurs frequently enough to derail students' understanding (Bowen & Roth, 1998). Gestures during instruction can be synchronous or asynchronous; therefore, students' cognitive attention must be devoted to tracking gestures along with the narrative instead of attending to the interpretation of the graph itself (Bowen & Roth, 1998). Students viewing a graph in class or lecture can be challenged by terms to define, relationships to understand, and scales to navigate, in addition to the gesticulations of their instructor (Bowen & Roth, 1998).

A lecturer possesses far more interpretive resources to make sense of graphs than most students (Bowen & Roth, 1998). Three levels of graph complexity were proposed by Glazer (2011) based on the number of variables shown and the degree to which domain knowledge is required for interpretation: simple--one or two variables and little domain knowledge; medium--more variables and some domain knowledge; complex--more variables with interactions between them, considerable domain knowledge, and advanced graph-reading skills. Also affecting the level of complexity are visual characteristics of the graph and the observers' prior knowledge, expertise, and associated skills.

The use of technology can potentially alter teaching methods for graphing and alter interpretation. Active graphing, entering data directly onto spreadsheets while inquiries are in progress, is an essential pedagogical tool. Where hand-drawn graphs emphasize neatness and details, computer-generated graphs can be bold and vigorous by effortlessly altering headings, labels, titles, and so forth. Such variety can work against students' understanding in that they focus more on the appearance of the graph as opposed to its content and meaning. Creating graphs with computers does not absolve students' need for graphic comprehension (Glazer, 2011). The use of animation provides information visually and explicitly, yet students have problems in perception and memory due to their transient nature, producing the misimpression of understanding (Ainsworth, 1999).

Task characteristics (creating a mental schema) are the underpinnings of graph comprehension. They include perceptual procedures of visually interpreting graphical displays of data and forming conceptualizations, initiating reasoning skills based on intuition (executing judgment of discrete variables), and combining personal understanding of the context with a mental model in order to respond appropriately to questions (Li & Goos, 2011). Li and Goos (2011) argued for the existence of a "syntax of graph perception" (p. 265) or a collection of ideas aligned along a continuum from most to least accurately understood interpretation of graphs. How quickly and accurately individuals interpret graphs is dependent on three fundamental codes and judgment tasks. The codes are "positioned along a common scale, length, and angle" and the judgments are of "discrimination, comparison, and proportion" (Li & Goos, 2011, p. 265). These code and judgment interactions are then used to explore basic graph-interpreting processes that involve "anchoring, scanning, projection, and superimposition and detection operators" (Li & Goos, 2011, p. 265). *Anchoring* is using a portion of the graph as a basis of the value of the entire graph. *Scanning* involves looking over the distance in the image being guessed at. *Projection* involves a comparison of two images by moving one and placing it over the other. *Superimposition* refers to moving parts of the image to a different part of the graph and placing it over that part. The function of detection operators is to compare the sizes of two parts in the graph, leading to simple answers such as increase, decrease, and remains the same (Li & Goos, 2011).

Li and Goos (2011) highlighted three processes as major actions in graph comprehension. Pattern recognition refers to a process whereby the visual impression of the graph is coded for. Interpretive processes are a function of pattern retrieval or pattern construction to discern quantitative and qualitative meaning. Integrative processes are cognitive functions that synthesize features of graphs like titles, labels, scales and so forth. The context and visual features of a graph need to be considered when translating the informational content of the graph into real-world conceptual understanding (Li & Goos, 2011).

Carpenter and Shah (1998) identified models of graph comprehension. The models occur in succession beginning with pattern recognition processes, followed by interpretive processes, then integrative processes perform the remaining tasks. There are overlapping processes within the integrative model that constitute two cycles. They are the recognition-interpretation cycle and the interpretation-integration cycle. The salient feature of pattern recognition processes is visual chunks. Working memory sorts and groups this visual input (Li & Goos, 2001). These bits of discernible information come in various shapes, patterns, colors, and so forth, which are then immediately transcribed into measurable and descriptive information by explanatory cognitive processes. If this does not happen, pattern recognition decays quickly. When information-laden visual chunks are available, there are sufficient patterns for accurate, rapid interpretation into meaningful information. The limited capacity of our brains to handle all of this graphical information at once leads to cycle repetition, which leads to more visual chunks available for interpretation (Li & Goos, 2011). The recognition-interpretation cycle is repeated until no unprocessed information remains.

Shah and Freedman (2011) also referred to “chunks” of data. The first chunk of data in graph comprehension deals with the visual elements, such as symbols, lines, and colors. These visual elements are influenced by bottom-up characteristics like format (i.e., bar or line graph). They recommended further research into how graph observers form visual chunks rooted in a variety of optical elements and the effect of the chunking process on data interpretation. They also believed that more research needs to be done with the Gestalt elements, proximity, similarity, and good continuity. Shah and Freedman (2011) further contended that Gestalt principles affect the comprehension of complex graphs, for example, depending on the layout of the graph, bar versus line, and how the viewer visually chunks the data.

Integration is necessary to complete the meaning-making cognitive process. The integrative processes relate meaningful information to the characteristics of the graph (labels, scales, title, and so forth). When the information is completely integrated with the descriptive features of the graph, the integrative processes are final (Li & Goos, 2011). Visual chunks resulting from the interpretation phase of the interpretation-integration cycle are made available for the integration phase of the cycle, leading to understandable information. The steps repeat until a logical interpretation is arrived at and the system is void of unprocessed information (Li & Goos, 2011).

Accurate graph construction is crucial to engage the interpretation-integration cycle. This includes utilizing an appropriate font, correctly choosing and labeling axes, appropriate scales, and layout. Data should be organized and presented as explicitly as possible in order to minimize mental calculations as well graph complexity (Li & Goos, 2011).

Bowen and Roth (1998) noted the significance of social context that enables data to be collected and graphs constructed and interpreted. These actions outweigh the interpretive action of an inanimate object. According to Bowen and Roth (1998), "Interpretations of a graph lie not in understanding the representation itself of a static object but rather in understanding the social actions through which the graph was originally constructed" (p. 86). True understanding of graphs and the meaning they hold is achieved through social interactions within a specific realm, subjugated by its inherent nature of enculturation of learning (Bowen & Roth, 1998).

Graphing Instruction

Previous research has identified numerous fault lines in reading graphs, including confusing slope with height and interval with point, the choice of how the data is displayed on the graph, and teacher expertise in teaching graphs (Glazer, 2011). Since graph creation and interpretation experiences complement each other, instructional order is a dilemma instructors must address.

Li and Goos (2011) summarized the stages of graphing as "construction, characterization, and inference" (p. 263). Construction is the hands-on phase involving the graph components, including scales, labels, plotting symbols, colors, and other elements. Characterization calls attention to the nature of the graph and its appearance: patterns or trends, gaps, or variations in the data. It also includes two implicit actions, reading within and between the data. Inference refers to the previously mentioned intuitive attributes: reading beyond the data to glean implicit meanings, formulate ideas and hypotheses, and anticipate the need for further efforts. Wavering

(1989) found that student responses to graph interpretation questions had implications for teaching graphing, specifically that data need to be readily scaled and ordered, data should be generated from student experiments, and students should manually create graphs and not be reliant upon computer generation in order to improve their logical development.

Much effort has gone into determining where the failure of graphing instruction takes place and where corrective action should occur. Some researchers believed that a portion of students are graphically challenged and may have never have been asked what the line on a graph represents (Connery, 2007). For these students, “patterns, trends, centers, clusters, gaps, outliers, spreads and variations” constitute the morass they find themselves in (Connery, 2007, p. 262). Reasoned judgment is the mechanism students must harness in order for “comparison, proportion, and discrimination” to make sense of it all (Li & Goos, 2011, p. 262). When students are engaged in making graphs, they frequently fail to grasp the function of each part of the graph. This can result in charts and graphs that are incorrect. Li and Goos (2011) argued for explicit instruction on graph autonomy, about “title, axis labels, scales, caption, content of a graph” (p. 262) in illustrating data features and connections.

Students’ difficulties with graphs fall into categories such as distinguishing slope from height and interval with point, regarding graphs as pictures, and perceiving graphs as a collection of discrete points (Glazer, 2011). Even when graphs are built correctly, their meaning frequently evades students because they have difficulty discerning the obscure relationships within the data. When students focus on the mechanics of creating graphs, the graph’s importance is negated by their inability to correctly interpret its meaning (Li & Goos, 2011).

There are conflicting findings regarding student difficulties with determining slope and y-intercept (Hattikudur et al., 2012). One set finds that students have a more difficult time with slope because it makes more cognitive demands as it involves manipulation of two points as opposed to one point to determine the y-intercept. However, Hattikudur et al. (2012) found that students have an easier time with slope because it translates into familiar real-world experiences versus counterintuitive events with y-intercept. Understanding the concepts of slope and y-intercept improved in students from sixth grade through eighth grade, yet understanding of the y-intercept consistently lagged behind. One possible explanation for this might be students' prior knowledge of slope and being able to successfully transfer it from their knowledge of slope in tables to their understanding of the concept of slope in graphs (Hattikudur et al., 2012).

Differences in students' cognitive ability with graphs may stem in part from an imbalance of instructional attention to slope and y-intercept where more time is spent on the prior than the latter (Hattikudur et al., 2012). This difficulty with y-intercept manifested itself when it came to constructing qualitative graphs. The numerical features of quantitative graphs provided students a foothold in graph analysis and an advantage in overall comprehension when compared to qualitative graphs (Hattikudur et al., 2012). A possible answer to this dilemma would be to provide adequate graphing practice with both quantitative and qualitative data, thereby allowing students the chance to experience both process and object perspectives when graphing linear functions (Hattikudur et al., 2012).

There are other phenomena that also affect student graphing comprehension. Sharma (2006) concluded that students were frequently at a loss as to how and when to utilize previously instructed data manipulation techniques such as mean, median, and mode. Inadequate classroom instruction and practice may produce limited student understanding. Sharma (2006) found that students' difficulties also occurred when their decision making was influenced by comparisons between data and students' own past experiences. In Sharma's 2006 study, students attempted to make connections between class instruction and personal experience. Sharma found that students would ignore the obvious indication of the data in preference for an explanation based on their own personal or school experiences in a phenomenon identified as "context denial" (Sharma, 2006, p. 257). Students' reasoning was inconsistent as a result of conflicts between their experiences and the data. Student interviews substantiated this finding. Students gave correct answers to graphing questions, but for the wrong reasons. Student interviews revealed that each child personalized the context differently and therefore arrived at different interpretations and conclusions from others. Students need classroom instruction in graph construction and interpretation within a familiar context in order to master graphing and transfer it between settings (Sharma, 2006).

In a 2005 study, Sharma (2006) noted a phenomenon called *negative transfer* when students would find a pattern in a graph and erroneously assume that all graphs should have patterns. Students should be encouraged to be active participants in data collection and should be able to relate the connections and arrangements they find in their data (Sharma, 2006). Broadening students' involvement with information collection and manipulation will lead them toward becoming proficient at reading data (Sharma, 2006). Effective graph utilization must extend beyond merely taking data directly from a graph. It should also include analysis and interpretation within a social context (Sharma, 2006).

Teacher facility with graphs directly influences student understanding. Sharma (2006) found that in order to address the issue of student difficulty with graphing, teachers must be aware of student conceptions and misconceptions brought into the classroom and be prepared to offer alternatives. Glazer (2011) found that despite considerable preparation, preservice teachers still had difficulty using a graph to answer questions about relationships between variables. The study concluded that prospective teachers need more experience engaged in graphic analysis. The study also proposed that these very same teachers might be contributing to problems of implementing inquiry-based lessons.

With graph skills, as with science literacy and literacy in general, exposure, preparation, and expectations are key ingredients in providing students with necessary experience. Student difficulty with graphing may be a literacy issue and lie with students not understanding questions being asked and their limited experience in providing explanations. Teachers may be complicit by being less than clear about the questions they are asking (Sharma, 2006). This absence of experience broadens as students proceed along the graphing continuum. When students reach postsecondary levels, their affiliation with the graphing community becomes one of being a member versus a nonmember. Membership status adds another variable to the milieu of graph comprehension.

Current research in graph instruction has focused on specific moments in time instead of an intervention monitored over a period of time (Connery, 2007). As an improvement to present teaching models, Connery (2007) suggested that students predict what they think the data will look like before the experiment is performed, then sketch a graph of their prediction. Graphing predictions can begin as early as middle school and continue throughout the educational process.

Students' initial foray into graphing predictions would happen with teacher direction. Students decide on the dependent and independent variables and then select a graph best resembling the data from an array of graphs presented by the teacher (Connery, 2007).

Conclusion

Viewing graphical data and processing it in the brain generates comprehension and deep perception of the data. Ultimately, interpretation of graphically represented data lies with students' interaction with it: how they visually acquire and construe the data and how they mentally manage and analyze the data. For students to have facility with complex quantitative information from graphs, it is not enough for them to simply read "within the data," especially when their interpretive skills are far weaker in the sophisticated processes of reading "between" and "beyond" the data (Li & Goos, 2011, p. 272). The ultimate goal of using graphs to use and interpret data goes beyond pedestrian steps to incorporate more cerebral tasks. According to Li and Goos (2011), "in addition to pattern recognition, graphical comprehension involves processes of judgment, synthesis and inference" (p. 272).

Our general investigation of scientific instruction with graphs yielded the following information:

1. Scientific graphing is instructed through the use of microcomputer labs which allow immediate feedback to students.

2. Student graphing skills are assessed with both multiple choice and free response instruments.

3. Hard science journals publish more graphs than soft sciences.

4. School science graphing lacks resources for the complex understanding that is available with real-world science graphing.

5. Graph interpretation is a function of the graph's characteristics, viewers' knowledge about graphing, and viewers' knowledge about data in the graph.

6. Graphs assist understanding by providing additional visual cues to supplement textual information.

Based on our review of the literature on how to teach scientific graphing, we concluded that graphs need to be taught without ambiguity due to their explicitness and significance. The largest obstacle in research lies in understanding graph usage. Studies tend to look at specific moments in time rather than interventions followed over a period of time (Glazer, 2011). Interpretation of graphs depends on the graph's format, the observer's background knowledge of the graph's content, and the level of graphing skills of the viewer (Shah & Freedman, 2011). Table 1 lists the issues on graphing elaborated upon in this review.

Table 1

Graphing Problems and Solutions

Problems	Solutions
Student literacy	Have students make predictions about what the data will look like BEFORE
Negative transfer	Use authentic data
Context denial	Have students participate in data collection
Higher order: interpreting and predicting	Real-life situations
Struggle with math/algebra; link between scientific inquiry and algebraic reasoning	Have plenty of opportunities to collect data and graph
Background knowledge and/or personal experience and/or intuition	Multi-modal interactions - body kinesthetics
Inconsistent reasoning	Social interactions for data collection and graphing
Wrong strategies - comparing high/low values, ranges	MBL
MBL	Other representational forms: pie charts, histograms
Data tables	Teacher explicit instruction
Common data manipulation: mean, median, mode	Pattern recognition “chunks”
Visual representation	
Distinguishing slope from height	
Distinguishing interval from point	
Regarding graphs as pictures	
Perceive graphs as collection of discrete point	
Patterns - looking for them when they are not there, not seeing them when they are	
Qualitative versus quantitative	
Gestalt	
Proximity, similarity, and good continuity	
Teacher	
Ineffective preparation (for lab)	
Failure to explicitly connect science and math	
Asynchrony	
Deficit in training	
Student	
Membership	

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